EV316935980

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

APPLICATION FOR LETTERS PATENT

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ELECTRICAL POWER DISTRIBUTION CONTROL SYSTEMS AND PROCESSES

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ATTORNEY'S DOCKET NO. PC1-004
ELECTRICAL POWER DISTRIBUTION CONTROL SYSTEMS AND PROCESSES

CONFIDENTIAL

RELATED APPLICATION DATA

[0001] This application is related to U.S. Patent Application No. 10/117,723, filed on April 1, 2002, published as Published U.S. Patent Application No. 20030187550 A1 on October 2, 2003, entitled "Electrical power distribution control systems and processes", listing T. Wilson and K. Hemmelman as inventors and which is assigned to the assignee of this application, the disclosure of which is hereby incorporated herein by reference.

TECHNICAL FIELD

[0002] The disclosure relates to electrical power distribution systems, processes and apparatus and power management in power distribution systems. More particularly, the present disclosure relates to power conservation and selective power regulation in power distribution systems.

BACKGROUND

[0003] In electrical power distribution systems, several needs compete and must be simultaneously considered in managing electrical power distribution. A first concern has to do with maintaining delivered electrical power voltage levels within predetermined limits. A second concern relates to overall efficiency of electrical power generation and distribution. A third concern

relates to these and other concerns in light of changing electrical loading of the system and variations in the character of the loading. A fourth concern relates to power system management under conditions associated with an increased probability of compromise of large scale ability to deliver appropriate power.

[0004] It is generally desirable to manage a power grid to reduce overall power consumption while maintaining adequate delivered voltage minimum and maximum levels across the system. In other words, the voltage levels actually delivered to various users need to be kept within predetermined limits while delivering power efficiently, without undue power loss in the delivery system or power grid, including the power generation equipment. As power usage within the system changes, in accordance with diurnal, weekly and seasonal factors, among others, need for regulation of power distribution changes as well. To an extent, some of these changes are reasonably predictable, however, other aspects of these changes may not be readily predictable.

[0005] Predictable changes in system loading are forecast by integrating power demand over time and considering this draw together with other factors, such as increased outdoor temperature and known diurnal variation patterns. For example, when summer heat results in increased power demand for air conditioning during the course of the day, fast food power demand associated with the

end of the work day may indicate that a power shortage is imminent. Typically, measurements of power demand and delivered voltage are made every few seconds, filtered to reveal variations with periodicities on the order of a few minutes or longer, and adjustments to voltage are made perhaps once or twice an hour. This is called "conservation voltage reduction" and is intended to reduce overall energy demand.

[0006] However, compromise of power delivery capability due, for example, to extreme weather conditions (e.g., gale winds affecting the distribution system) or unforeseen decrease in available power (e.g., generator malfunction) is not necessarily amenable to precise forecasting but is observable. As a result, there is need for dynamic system adjustment in response to observed changes in system capacity, conditions and loading.

[0007] Increased probability of compromise of large scale ability to deliver appropriate power may include increased probability of system-wide failure or blackout of an area, where "system-wide failure" could mean either a large grid being shut down or a smaller grid being isolated from a larger grid, with a potential result that the smaller grid then would be shut down or malfunction. In some cases, grid failure may be caused by automated shutdown of one or more generators in response to

determination of grid conditions ill-suited to the generator in order to obviate catastrophic generator failure.

[0008] The conditions associated with an increased probability of compromise of large scale ability to deliver appropriate power are varied, and can range from "brownout" situations to complete disruption of electrical service or "blackouts". Some types of power consumption relate to relatively vital concerns, such as hospitals, infrastructural support systems (telephone, police, fire protection, electrical traffic signals and the like) and others relate to more quotidian concerns, such as air conditioning, fast food operations and industrial operations such as aluminum smelters and the like, as equipment is added to or removed from service, for example.

[0009] The latter types of concerns can present a high electrical draw at certain times of day. However, interruption of power delivery to such operations does not usually present life-threatening consequences when such operations are without electrical power.

[0010] Further, in the event of severe disruption or demand, grid systems used for delivery of electrical power can experience catastrophic failure when load conditions presented to generators in the system are such that one or more electrical generators are automatically shut down or disconnected from the system. This situation obviously places increased demand or even less suitable loading conditions on other generators or grids to which the grid is

coupled. As a result, other generators or grids coupled to the affected grid may disconnect from the affected grid, potentially resulting in a blackout. Such blackouts can be extremely widespread in electrical generation and distribution systems employed multiple coupled grids each having electrical generation capability.

[0011] Prior art power regulation systems include fusing, opening switches at a power station or substation to remove load components, or sending out trucks with technicians to manually open switches to remove portions of the load from the system, or to manually adjust power regulators and set points. These methods are not amenable to rapid, dynamic load adjustment or rapid, dynamic power management.

[0012] Another prior art system provides equipment at the user site that disables high load appliances, such as hot water heaters, on demand. This may be based on forecasting of anticipated excess demand. Such systems are known as "demand side control" systems. These tend to be expensive, in part because the number of control switches is high.

[0013] Needed are systems, apparatus and processes for (i) optimizing efficiency of power delivery while maintaining delivered voltage levels within acceptable limits under changing conditions for electrical power demand and (ii) coping with conditions associated with an increased probability of compromise of large scale ability to

deliver appropriate power in such a way as to avoid compromise of critical concerns and to further avoid catastrophic electrical system failure.

SUMMARY

In one aspect, the present disclosure describes a process for power distribution regulation. The process for power distribution regulation includes filtering data from electrical sensors to provide conditioned data representative of a portion of a power distribution grid and determining, by a controller and based in part on the conditioned data, when an increase or decrease in an output parameter from one regulator of a plurality of regulators in the power distribution grid will reduce system power consumption. The process also includes increasing or decreasing the associated output electrical parameter in response to the controller determining that such will reduce system power consumption.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Fig. 1 is a block diagram of an electrical power distribution system, which is an exemplary environment suitable for implementation of the presently-disclosed concepts.

[0015] Fig. 2 is a block diagram of a power controller useful in the system of Fig. 1.

[0016] Fig. 3 is a block diagram of an example of a portion of a power distribution system using the power controller of Fig. 2.

[0017] Fig. 4 is a flow chart of a process for managing the electrical power distribution system of Fig. 1.

[0018] Fig. 5 is a flow chart of a process for operating the power controller of Fig. 2.

[0019] Fig. 6 is a flow chart of a process for managing the electrical power distribution system of Fig. 1.

[0020] Fig. 7 is a flow chart of a process for stabilizing the electrical power distribution system of Fig. 1.

[0021] Fig. 8 is a graph of amplitude and phase response for a lowpass filter.

DETAILED DESCRIPTION

Introduction

[0022] Methods and apparatus for implementing stabilized closed-loop control of delivered voltage in electric power distribution systems are disclosed. The disclosed concepts facilitate regulation of the delivered distribution voltage within predefined bounds, consistent with the adjustment capabilities of regulators such as regulating transformers.

Environment

[0023] Fig. 1 is a block diagram of an electrical power distribution system 10, which is an exemplary environment suitable for implementation of the presently-disclosed concepts. The power distribution system 10 includes a power station 12, that may be coupled to a power source or sink via a high voltage bus 14. In one embodiment, the power station 12 includes one or more generators. In one embodiment, the power station 12 distributes power delivered via the bus 14. In one embodiment, the power station 12 delivers power to other power distribution systems via the bus 14. As will be appreciated, the role of the power station 12 may change with time and demand, i.e., it may supply excess power to other systems when local load conditions permit and it may be supplied with power at other times when local load conditions require such.

[0024] The power station 12 includes one or more group controllers 16. Power is distributed via buses 18 from the power station 12 to one or more substations 20. In turn, each substation 20 delivers power further "downstream" via buses 22. It will be appreciated that a series of voltage transformations are typically involved in transmission and distribution of electrical power via the various power stations 12 and substations 20 and that the system 10 being described exemplifies such systems that may include additional or fewer layers of transformation and distribution.

[0025] The substation 20 delivers electrical power via buses 22 to one or more power regulation devices 24, which may include a local controller 26. In turn, the power regulation devices 24 deliver electrical power further downstream via buses 28. Ultimately, electrical power is coupled to a sensor 30 and/or to a user 32. Sensors 30 tend to be associated with critical loads such as hospitals.

[0026] In one embodiment, the electrical power is coupled to a sensor 30 capable of determining electrical parameters associated with power consumption and transmitting those assessed parameters to the associated local controller 26 and/or to the group controller 16. It will be appreciated that any medium suitable to data transmission may be employed, such as radio links, which may utilize spread spectrum coding techniques or any suitable modulation of spectrum management methods suitable for data communications, point-to-point radio links, fiber optical links, leased lines, data signals coupled via power lines or buses, telephone links or other infrastructural data communications paths. In some embodiments, such may also be conveniently collateral to power distribution system elements (e.g., coaxial cables employed for data transmission such as are often employed in cable television systems).

[0027] In one embodiment, the sensor 30 measures voltage and is also part of an electrical meter used for measuring the amount of electrical power used and thus for determining billing data, such as a conventional

Automatic Meter Reader or AMR. In one embodiment, the sensor 30 is equipped to assess line voltage delivered to the user 32, or "delivered voltage". In one embodiment, the sensor 30 is equipped to measure current.

[0028] In one embodiment, the local controller is configured to respond to several associated sensors. This may be accomplished by dynamically determining which one or ones of an associated plurality of sensors is providing data most relevant to determining how to most effectively adjust the associated output electrical parameter. Effective control of power delivered by the associated power regulation device 24 is determined by selecting between the associated sensors, dependent upon changes in current draw in different loads controlled by the power regulation device 24, load shifts or voltage changes. In one embodiment, the selection tends to be responsive to the sensor that results in optimal power conservation.

[0029] In one embodiment, the sensor 30 is equipped to assess power factor, also known as VAR or Volt Amperes Reactive, that is, the phase shift induced by inductive or capacitive loads. Power factor can be significant because transmission losses known as I^2R losses can increase when the currents associated with driving the load increase without necessarily delivering more total work to the load.

[0030] These losses can result in situations where the total power demanded from the power station 10 or substation 20 actually

decreases when line voltage to the user 32 increases. One example of such a situation is where the load is highly inductive and the amount of work accomplished is controlled primarily by the amount of current drawn by the load, e.g., loads including electrical motors.

[0031] Conventional power distribution systems provide some correction of or management of power factor or VAR by switching reactive elements, such as shunt capacitors, into or out of the system at strategic locations. These conventional systems do not attempt to reduce losses by voltage adjustment.

[0032] Conventional Supervisory Control And Data Acquisition (SCADA) systems have not in past been associated with incremental voltage controllers. In particular, such systems have not been affiliated with controllers that are equipped to test for conditions where an increase in delivered voltage can reduce overall power consumption by providing improved power factor.

[0033] In the presently-disclosed system, such a controller advantageously also effectuates data collection and logging. In one embodiment, at least the group controller 16 records a conventional system data log for tracking voltage, current, kiloWatt hours and power factor or kilo volt-amp reactive power and the like over time. In one embodiment, at least the group controller 16 records a conventional event log for tracking load tap control data, voltage regulation data and breaker operations and the like over time. In one

embodiment, at least the group controller 16 records a conventional status log for tracking position of load tap controls, voltage regulator setting, breaker settings and the like over time.

[0034] In one embodiment, at least the group controller 16 records minimum and maximum values for conventional electrical parameters such as voltage, kiloWatt flow, KVAR and the like versus time. In one embodiment, such conventional data are collected at regular intervals, such as every thirty seconds or every minute. In one embodiment, additional such conventional data logs are recorded by local controllers 26 as well.

[0035] Fig. 2 is a block diagram of a power controller 24 for use in the system 10 of Fig. 1. The power controller 24 includes the local controller 26 of Fig. 1. The local controller 26 is linked to the group controller 16 via a data path 34 and is linked to the downstream sensors 30 of Fig. 1 via a data path 36. The power controller 24 accepts input electrical energy V_{IN} via a bus 38 that is coupled to a voltage regulator 40. In one embodiment, the voltage regulator 40 comprises a conventional autotransformer employing a make-before-break variable tap that is set in conformance with command signals communicated from the local controller 16 via a data path 42.

[0036] The power controller 24 also optionally includes a data path 44 coupled to switches 46. The switches 46 couple elements 48

for power factor management into or out of the circuit in response to commands from the local controller 26. In one embodiment, the elements 48 comprise conventional capacitors that are switched into or out of the circuit in conformance with commands from the local controller 26.

[0037] A sensor 50 is coupled to the local controller 26 via a data path 52. The sensor 50 measures electrical parameters associated with electrical energy leaving the power controller 24, such as kiloWatt hours, current, voltage and/or power factor. The power controller 24 delivers electrical energy V_{OUT} for downstream distribution via a bus 54.

[0038] In one embodiment, the local controller 26 regulates power delivery subject to overriding commands from the group controller 16. In one embodiment, the power controller 24 increments (or decrements) line voltage at the 120/240 volt distribution level. In one embodiment, the power controller 24 changes output voltage in increments of 5/8 %, or about .75 volt steps at the 120 volt level. In one embodiment, when larger changes in voltage are desirable, the power controller 24 allows a stabilization interval of between forty seconds and two minutes between an increment and evaluation of system parameters prior to making a next incremental voltage change.

[0039] In one embodiment, the power controller 24 maintains delivered line voltage in band of voltages ranging from about 110 volts or 114 volts to about 126 volts to 129 volts, with 117 volts being exemplary, and with a reduced level of about 110 to 100 volts being applicable in emergency or brownout situations.

[0040] In one embodiment, multiple power controllers 24 are situated downstream of a master controller 24. For example, in aluminum smelting plants, such an arrangement may be advantageous in order to provide a recommended voltage or current to the smelting pots, and to optimize energy costs.

[0041] In silicon refining plants, power control can be crucial to maintaining the melt at the appropriate temperature and also for maintaining an appropriate rotation speed in Czochralski crystal growth apparatus. As a result, the criticality of power regulation depends on the end use to which the user puts the power. Programming parameters used in the local controller 26 of the power controllers 24 can be set in light of these needs to effect the desired power regulation.

[0042] In some power distribution situations, power control is important because the contractual arrangements between the user and the service provider result in increased power rates for a period, such as a year, if a maximum or peak amount of power contracted for is

exceeded even once. Accordingly, such users have incentives to regulate power use to obviate exceeding that contractual amount.

[0043] Fig. 3 is a block diagram of an exemplary system 60 illustrating application of the power controller 24 of Fig. 2. In the exemplary system 60, electrical power is distributed at a first voltage, such as 115 kiloVolts, over bus 62. The electrical power is stepped down to a reduced voltage, such as 12.5 kiloVolts, by a transformer 64, and is transmitted downstream via a bus 66. A billing meter 68 may be coupled to the bus 66. The local controller 26 includes one or more processors 69.

[0044] Taps 70 and 72 are coupled to a power monitor PM 74 in the local controller 26 to allow the processor 69 to monitor electrical parameters associated with the power controller 24. In one embodiment, the power monitor PM 74 monitors voltage. In one embodiment, the power monitor PM 74 monitors power factor. In one embodiment, the power monitor PM 74 monitors electrical power. In one embodiment, the power monitor PM 74 monitors current. A conventional recloser or circuit breaker 76 is coupled in series with the bus 66 and is coupled to the processor 69 in the local controller 26 via a data path 78, allowing monitoring and/or control of the recloser 76.

[0045] The processor 69 in the local controller 26 is coupled to the group controller 16 (Fig. 1) via data path 34. In this example, a conventional modem 79 is employed for bidirectional data transfer.

[0046] A voltage regulator 80 is coupled in series in the bus 66. The voltage regulator 80 is responsive to control signals delivered from the processor 69 in the local controller 26 via a data path 82, and the local controller 26 also is able to collect status data from the voltage regulator 80 via this data path.

[0047] Electrical power is then transferred downstream via the bus 66, which may include line voltage monitors LVM 84 disposed at strategic intervals and in data communication with the local controller 26. In one embodiment, a step-down transformer, instrument transformer, potential transformer or transducer 86 located near the point of use transforms the intermediate voltage employed on the bus 66 to voltages suitable for sensing equipment such as a sensing module 88. The device 86 is calibrated to permit readings corresponding to user voltages but is not necessarily as precise as transformers used to transform intermediate transmission voltage levels to end use voltage levels or in conjunction with power metering purposes.

[0048] The module 88 for measuring electrical parameters associated with delivered power and/or voltage is typically located at or near the transformer or device 86, between or near the transformer

or device 86 and the end user 32 (Fig. 1), and may include power measurement devices PMD 89 for billing purposes. The module 88 is in data communication with the local controller 26 via a data path, in this example, via a radio 90 that exchanges radio signals with a radio 92 that is coupled to the processor 69 in the local controller 26.

[0049] Data communications via the various links may be effected using any known or conventional data transfer protocol and method, e.g., may be signals transmitted using American Standard Code for Information Interchange (ASCII) via an RS-232 or EIA 485 serial data signalling standard, for example with the data transfer transactions managed by the DNP3 utility data communications protocol.

[0050] Fig. 4 is a flow chart of a process P1 for managing the electrical power distribution system of Fig. 1.

[0051] The process P1 begins with a step S1. In the step S1, the local power controller 24 of Figs. 1 through 3 increments or decrements at least one parameter associated with electrical power that is being distributed, such as line voltage. The process P1 then waits for a predetermined interval for the system to settle, which, in one embodiment, may range from about forty seconds to two minutes.

[0052] In a query task S2, the process P1 determines if the actions taken in the step S1 resulted in a decrease in power

consumption. When the query task S2 determines that the actions taken in the step S1 resulted in an increase in power consumption, control passes to steps S3 and S4. When the query task S2 determines that the actions taken in the step S1 resulted in a decrease in power consumption, control passes to a step S5.

[0053] In the step S3, the actions taken in the step S1 are reversed. In other words, when the query task S2 determines that overall power consumption increases when the voltage decreases, the power controller 24 then returns to that voltage setting initially present and waits for the system to settle in the step S3. The process P1 then increases the voltage in the step S4 and again waits for the system to settle. Similarly, when the query task S2 determines that overall power consumption increases when the voltage increases, the power controller 24 returns to that voltage setting initially present and waits for the system to settle in the step S3. The process P1 then decreases the voltage in the step S4 and again waits for the system to settle. Following the step S4, control passes back to the query task S2.

[0054] The increments in voltage are subject to predetermined voltage maximum and minimum values, which may in turn depend on or be changed in response to system conditions. In other words, if the voltage is initially at the predetermined minimum, the process P1 tests the system with an increase in voltage but not a decrease.

[0055] When the query task S2 determines that the power consumption has decreased, the process P1 iterates the steps S1 and S2 (which may include steps S3 and S4) in a step S5. The iteration of the step S5 continues until no further decrease in power consumption is observed. In other words, the process P1 determines a line voltage consistent with reducing overall power consumption.

[0056] The process P1 then sets the line voltage to the optimum voltage or the voltage at which minimum power consumption occurred in a step S6. The process P1 then ends.

[0057] Fig. 5 is a flow chart of a process P2 for operating the power regulation devices 24 or the local controller 26 of Fig. 2. The process P2 begins with a query task S21.

[0058] In the query task S21, the process P2 determines when a predetermined interval has passed without a voltage adjustment occurring. In one embodiment, the predetermined interval is in a range of one half hour to one hour.

[0059] When the query task S21 determines that such an interval has not passed without a voltage adjustment, control passes back to the step S21. When the query task S21 determines that such an interval has passed without a voltage adjustment, control passes to a step S22.

[0060] In the step S22, a first power consumption level is measured. Control then passes to a step S23.

[0061] In the step S23, the power controller 24 adjusts a line voltage within predetermined limits and then waits for a predetermined interval for the system to settle. In one embodiment, the predetermined settling interval is in a range of from forty seconds to two minutes. Control then passes to a step S24.

[0062] In the step S24, a second power consumption level is measured. Control then passes to a query task S25.

[0063] In the query task S25, the process P2 determines when the second power level is less than the first power consumption level. When the query task S25 determines that the second power consumption level is less than the first power consumption level, control passes to a step S26. When the query task S25 determines that the second power consumption level is greater than the first power consumption level, control passes to a step S27.

[0064] In the step S26, the process P2 iterates the steps S22 through S25 to determine a line voltage associated with optimal power consumption levels and set the voltage to this level. The process P2 then ends.

[0065] In the step S27, the process P2 iterates the steps S22 through S25 but with the increment reversed from the increment or decrement employed in the first instantiation of the step S22. Control then passes to a step S28.

[0066] In the step S28, the process P2 determines a voltage for optimal power consumption in the system and sets the voltage to that level. The process P2 then ends.

[0067] Fig. 6 is a flow chart of a process P3 for managing the electrical power distribution system of Fig. 1. The process P3 begins in a query task S31.

[0068] In the query task S31, a group controller 16 determines when conditions associated with an increased probability of compromise of appropriate delivery of electrical power are present.

[0069] This may be forecast from observed power consumption trends and knowledge of prevailing conditions, analogous to situations invoking conventional power peak demand management techniques such as demand control, or it may be due to observable emergency electrical disturbance caused by a catastrophy of one sort or another. These kinds of situations have been dealt with in past using ON/OFF switching of one sort or another for shedding portions or all of the load.

[0070] When the query task S31 determines that such conditions are not present, the process P3 ends. When the query task S31 determines that such conditions are present, the group controller 16 transmits signals to local controllers 26 to cause them to set the power controllers 24 to predetermined values consistent with

reduction of system power requirements in a step S32. Control then passes back to the query task S31.

[0071] For example, when the system is subject to severe loading, delivered voltage reduction may be implemented. The initial delivered voltage might, for example, have been 117 volts. As the voltage is being incrementally reduced towards 110 volts (representing the lower setpoint), and the system is being monitored, a minimum in power consumption might occur at 112 volts. The controller of the present disclosure will locate this minimum and can set the delivered voltage to that value. When system conditions will not support system loading, even at the lower setpoint, the setpoints may be reset or other corrective actions described herein may take place, depending on circumstances.

[0072] The disclosed arrangement provides greater flexibility than prior systems in that incremental voltage or power adjustment is possible and practical, and may be automatically implemented. In one embodiment, and under appropriate conditions, some users, such as residential users and some types of commercial users, are denied power or are provided with reduced power at a first power level, while other users, such as hospitals, emergency facilities, law enforcement facilities and traffic control systems, are provided with power at a second power level that is greater than the first power level or are left at full power. In one embodiment, multiple tiers of

users are provided with various grades of power reduction or non-reduction.

[0073] In some areas, hydroelectric or other electrical power generation systems have been extensively developed, while other areas may not lend themselves to such development. One example of the former occurs in the Pacific Northwest, where hydroelectric power generation capabilities have been extensively developed. As a result, power generation facilities in the Pacific Northwest are able to produce more power than may be needed in that geographical area from time to time.

[0074] A delivery area such as California, on the other hand, has extensive power needs but has limited ability to produce electrical power, and is bordered by desert areas that also do not lend themselves to hydroelectric power production. Thus, power stations in the Pacific Northwest may be able to, and in fact do, sell electricity generated in the Pacific Northwest to users in other places, such as California.

[0075] This leads to some fluctuations in demand in the Pacific Northwest power generation stations. At times, reductions in demand in the generation area (in this example, the Pacific Northwest) require that the system dissipate some of the electrical power that is generated there in order to preserve synchronization of the generators with each other and with other portions of the grid.

In at least some cases, this need to dissipate electrical power is met by coupling large resistors across the generators. Typically, these are very large conventional nichrome wire resistors.

[0076] In some situations, the need to slew power into these resistors can arise rather abruptly. For example, when weather-, earthquake-, fire- or vehicular-driven events damage a portion of the distribution infrastructure in the delivery area or between the delivery area and the generation area, rapid changes in system dynamics are possible.

[0077] However, the controllers 16 and 24 of the present disclosure can be advantageously employed to increase voltage that is delivered in the generation area and in other portions of the grid that is serviced by generators in that area. The controllers 16 and 24 can adjust delivered voltages upward but stay within the predetermined limits appropriate for normal power service. As a result, system stability is increased.

[0078] Fig. 7 is a flow chart of an exemplary process P4 for stabilizing the electrical power distribution system 10 of Fig. 1 using controllers such as 16 and 24.

[0079] The process P4 begins with a query task S41. In the query task S41, the process P4 determines when an increase in delivered voltage, within the predetermined voltage setpoints, will result in improved stability for the system 10.

[0080] When the query task S41 determines that an increase in voltage is appropriate for improving stability of the system 10, control passes to a step S42.

[0081] In the step S42, a controller in the system such as the group controller 16 increases voltage delivered to the users 32. Typically, the increase in voltage is incremental, as discussed hereinbefore, and is followed by a predetermined settling period and then data collection regarding system parameters. Control then passes back to the query task S41 to determine if another increase in voltage is appropriate for the system 10.

[0082] When the query task S41 determines that an increase in voltage is inconsistent with an increase in stability of the system 10, or is not appropriate for such system 10, control passes to the query task S43.

[0083] In the query task S43, the process P4 determines when a decrease in delivered voltage is appropriate for increasing stability for the system 10 and is consistent with the predetermined setpoints. When the query task S43 determines that a decrease in delivered voltage is appropriate for increasing system stability, control passes to a step S44.

[0084] In the step S42, a controller in the system such as the group controller 16 decreases voltage delivered to the users 32. Typically, the decrease in voltage is incremental, as discussed

hereinbefore, and is followed by a predetermined settling period and then data collection regarding system parameters. Control then passes back to the query task S41 to determine if an increase in voltage is appropriate for the system 10. The process P4 then ends.

[0085] It will be appreciated that the processes P1 through P4 are cooperative with each other and with other processes carried out in the system 10. For example, when the system 10 no longer poses a stability issue, the process P4 may be terminated and power control may be determined by other factors in the system. Additionally, the processes P1 through P4 are structured to maintain delivered voltage at an appropriate level, such as within a range determined by programmable setpoints. Processes P1 through P4 may employ suitable methods from the engineering arts of automatic control theory and signal processing, including filtering, system identification, and prediction or extrapolation methods.

[0086] From the foregoing, it is apparent the present disclosure describes systems, processes and apparatus which can be utilized to monitor and manage electrical power distribution. Further, the disclosed systems, processes and apparatus permit power conservation and also can provide more robust power delivery under inclement power system loading conditions. In addition, the systems, processes and apparatus of the present disclosure are cost effective when compared with other power management devices.

[0087] Empirical studies have shown that overall system operation may be improved by incorporating signal processing and conditioning techniques, prediction of load variations based on measured and recorded system operation parameters and known ambient condition variation patterns affecting energy demand.

[0088] For example, the voltage regulator 40 of Fig. 2 is generally capable of a finite number of switching events during the useful life of the regulator 40.

[0089] Typical voltage regulating autotransformers operated by the electric utilities effect changes to their output voltage by mechanical selection of predetermined winding taps. The mechanical selection process limits the effective operating duty cycle and the useful life of the regulator. As a result, it is desirable to implement a scheme which controls the delivered voltage such that energy conservation or other objectives are achieved while operating the voltage regulators in a manner that is consistent with their limitations.

[0090] Additionally, the response time of such regulators 40 does not favor attempting to correct high frequency "spikes" such as may result from switching of high draw loads such as large motors. As a result, filtering signals derived from the sensors 30 of Fig. 1 to limit frequency of voltage adjustment by the regulators 40 to about twelve to fifteen switching events per day provides improved system

operation. Accordingly filtering operations may be applied to the sensed signals to improve system operation; in the present context, low-pass filtering is indicated.

[0091] Delay behavior in filtering operations affects control system operation and thus design. In many closed loop control applications, including certain process control problems in which well-behaved step response is desirable, filters manifesting constant group delay in the passband may be employed. In the present context, delivered voltage regulation is implemented using discrete tap selection in the final control element, resulting in small disturbances to the distribution circuits which are stepwise signals. Since stability of the controlled variable (the circuit voltage) is a design consideration in the automatic voltage control systems considered here, constant group delay low pass filtering may be usefully applied to the measured voltage signals.

[0092] In one embodiment, a discrete-time finite impulse response low pass filter having a linear phase response, a cutoff frequency of about 3 milliHertz and a constant total group delay of about 240 seconds implemented digitally as a cascade of filter sections provides effective signal conditioning. The cutoff frequency may be varied or tailored to specific applications based on knowledge of load characteristics.

[0093] A finite impulse response or FIR filter is a filter whose output signal x_n depends only upon prior observations of the input signal and may be modeled as $x_n = \Sigma b_i v_{n-i}$, where b_i represents filter coefficients and v_{n-i} represents input voltages. This type of filter is conveniently realizable as a two stage filter implemented as software using reduced precision compared to some other types of filters. For example, the IEEE 754 specification relates to single precision floating point implementation which can be achieved using a 24-bit (including one hidden bit) mantissa and an eight bit exponent, i.e., can be readily implemented using a 32-bit processor.

[0094] In a multiple stage filter, each successive stage operates at a slower sampling rate than the preceding stage, with the sampling rate determined by the spectral cutoff characteristics of the preceding stage. For example, the first stage may use a sample rate corresponding to one sample per fifteen seconds and may be an eighth or ninth order stage. The second stage may use a sample rate corresponding to one sample per 60 to 90 seconds, as determined by the cutoff frequency ω_c of the first stage, and may be a sixth order stage. The second stage would then provide an output signal every 240 to 300 seconds without aliasing. The filter design is motivated by a desire to achieve suitable spectral cutoff characteristics whilst reducing the overall group delay of the multistage system. In general, as filter order increases, filter delay increases and this may

have deleterious effects on closed-loop system stability, because closed loop control systems are susceptible to destabilization both by transport and other measurement delays and by signal artifacts introduced by sensors, transducers, filters or other signal processing operations in the measurement process. In this application, linear phase or constant group delay, whereby all passband spectral components of the measured voltage signals are delayed equally, corresponds to a lack of "ringing" that could otherwise result in system instability. In other words, linear phase finite impulse response filters can inhibit overshoot or ringing behavior. In this type of application, a lack of delay and amplitude distortion is important for stable system operation. An exemplary infinite impulse response filter characteristics suitable for such applications uses the Bessel characteristic, which provides a good approximation to linear phase delay in the passband.

[0095] Fig. 8 is a graph of amplitude 800 and phase 810 response for a lowpass filter. The amplitude response 800 shows a cutoff frequency ω_c which is defined as the frequency at which the filter response is one-half of the peak response value. The phase response 810 is linear.

[0096] Use of linear prediction techniques can improve system operation when such filtering is employed by allowing the system to effectively remove delays associated with the filter. These

techniques model the subject signal in a suitable parameter space, and generally such parameters are estimated continually during operation of the process or control system generating the subject signal. The estimation may be carried out by methods suited to the properties of the subject signals, such as end of line voltage, and may include such methods as gradient search, recursive least squares or Kalman filtering.

[0097] In turn, this can improve system stability and facilitate rapid system response in emergency situations. Linear prediction techniques treat the input signal as a Gaussian signal and assume that the signal is stationary over an interval. In this case, a signal variance that is constant over an interval of a half-hour is consistent with signal prediction over three to five minutes.

[0098] Linear prediction models comprise a class of methods employed for the temporal extrapolation of stationary signals. In such models, the one step ahead predicted value y_{n+1} of a signal y_n can be formulated as a function of a number of prior signal samples, or $y_{n+1} = \Sigma d_j x_{y-j}$, where the coefficients d_j depend on the statistics extracted from the signals and on the algorithm being employed, and are estimated using a process such as those noted supra.

[0099] In one embodiment, the system state vector for a regulated distribution feeder will contain the substation bus phase to neutral voltages, the end of line phase to neutral voltages, the

incremental energy delivered over a suitable sampling interval, the incremental reactive component of the apparent energy over the same sampling interval, the outside temperature at the substation in which the distribution feeder originates, the outside temperature at a selected end of line delivery point, and time of day. These signals contain the principal deterministic components of the delivered energy characteristics. The application of a recursive mean squared error estimator, such as the conventional Kalman Filter algorithm, provides estimates of the transitions matrices in the aforementioned state variable formulation. By using low-pass filtered signals in the state formulation and therefore the inputs to the state transition estimators, the forward predicted signals are thus future outputs of the filtered signals, which has the effect of reducing or eliminating the group delay of the filters.

[00100] In a similar embodiment which also utilizes a state variable formulation, the required state transition matrices are estimated by means of deconvolution, which is the conventional Ott-Meder prediction error filter algorithm.

[00101] An exemplary representation of one stage of such a filter is provided below in Table I.

Table I. Simplified representation of a single-stage predictor

$$\hat{\mathbf{V}}(k \mid k-1) = \mathbf{\Phi}(k, k-1)\,\hat{\mathbf{V}}(k-1 \mid k-1) + \mathbf{\Psi}(k, k-1)\mathbf{U}(k-1)$$

Quantity	Size	Interpretation
$\mathbf{V}(k)$	n x 1	System state vector (for example, line voltage)
$\hat{\mathbf{V}}(k \mid k-1)$	n x 1	Predicted state vector estimate at instant k
$\hat{\mathbf{V}}(k-1 \mid k-1)$	n x 1	Filtered estimate of the prior state vector $\mathbf{V}(k-1)$
$\mathbf{\Phi}(k,k-1)$	n x n	State transition matrix
$\mathbf{U}(k-1)$	m x 1	Known (measured) inputs vector
$\mathbf{\Psi}(k,k-1)$	m x n	Input transition matrix

[00102] An exemplary system thus might include a first low pass filter having an input coupled to an end of line voltage monitor and an output. A second low pass filter might have an input coupled to a measure of local temperature and have an output. FIR filter coefficients are supplied to the first and second filters. The first and second filter outputs are coupled to first and second inputs to a state vector processor V having an output. A Kalman filter estimator has an input coupled to the state vector processor V output and has a first output coupled to a third input to the state vector processor V. A second Kalman filter estimator output is coupled to a first input to a forward prediction output filter. A second input to the forward prediction output filter is coupled to the output of the first low pass

filter. An output from the forward prediction output filter provides a signal corresponding to feeder end of line RMS voltage having filtering and filter delay compensation characteristics, and this signal is then used in voltage regulator switching decisions for system stabilization and power conservation. The Kalman filter as described is an example of a more general form known as recursive predictors. In general, the predictions to be used are in the general class known as Fixed Lead Prediction. Connectionist structures (aka neural networks) can be applied as state predictors (like Kalman), using the same filtered inputs to predict 'filtered' outputs.

[00103] In contrast to prior art systems, the present systems, processes and apparatus provide great variability of system parameters, such as multiple, different delivered voltage levels, within predetermined limits. For example, all users can be incrementally adjusted up or down together, or some users may be adjusted to a first degree while other users are adjusted to another degree or to separate, differing degrees. Such advantageously provides new flexibility in power distribution control, in addition to providing new methods of adjustment.

[00104] In compliance with the statute, the subject matter has been described in language more or less specific as to structural and methodical features. It is to be understood, however, that the subject matter is not limited to the specific features shown and described,

since the systems, processes and apparatus herein disclosed comprise exemplary forms of putting the disclosed concepts into effect. The disclosed subject matter is, therefore, claimed in any of its forms or modifications within the proper scope of the appended claims appropriately interpreted in accordance with the doctrine of equivalents.